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Technical Note

# Study of neutron energy and directional distribution at the Beloyarsk NPP selected workplaces

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A B S T R A C T

Energy and directional distribution of neutrons at the Beloyarsk NPP workplaces is a subject of this study. Measurements of H*(10) rate and neutron energy distribution were taken at 8 workplaces, which can be divided into three categories: work with spent or fresh nuclear fuel, work with radionuclide neutron sources, work at the rooms adjusted to reactors. The Hp(10) measurements were performed only at 6 out of 8 locations, due to the fact that long term placing of an effective neutron moderator in fresh nuclear fuel storage facility is forbidden. As a result of the research energy and direction distribution of the neutron fields at 8 locations of the Beloyarsk NPP workplaces was obtained. To estimate the accuracy of the H*(10) rate and Hp (10) measurements the reference values of dose equivalents were calculated using energy and directional distribution. To take into account the difference between the reference values and the measured results site-specific correction factors were calculated.



## 1. Introduction

The ALARA (As Low As Reasonably Achievable) principle, formulated in 1954 by the International Commission on Radiological Protection to minimize harmful effects of ionizing radiation [1], is widely used at nuclear power plants (NPPs). This principle requires to maintain the lowest possible and achievable level of both individual (below the limits established by applicable standards) and collective radiation doses considering social and economic factors. Performing their work, NPP personnel is exposed to both external and internal exposure. Neutron and photon radiation are of the most interest because of their significant contribution to the summary exposure dose. Unlike photon radiation dosimetry, the dosimetry of neutron radiation is a difficult and completely unresolved task. The energy spectra of the real neutron fields in various areas of nuclear reactors and in rooms beside biological protection, as well as the neutron radiation spectra of fresh or/and used nuclear fuel and radioisotope sources, can be very diverse in form and ranges from hundredths of eV (thermal neutrons) up to units and tens of MeV (fast neutrons), i.e., at least 9 orders of magnitude. A wide range of neutron energies in most cases leads to the incorrect individual dose assessment for personnel since the energy dependence of individual dosimeters responses differs from the function of the individual dose equivalent per unit fluence. The most accurate estimates of an effective neutron dose for personnel can be obtained using the information on the neutron energy distribution at a personnel workplace. Measurement of the neutron field spectrum from various neutron radiation sources is a very complex and not fully resolved worldwide problem. Nevertheless, some studies of neutron energy distribution at workplaces have been performed in the European nuclear industry, mainly by EC-sponsored project EVIDOS [2–8]. EVIDOS project showed that neutron energy distribution at workplaces has a significant difference from place to place. Therefore, personal dosimeters are highly recommended to be used taking into account the site-specific correction factors.

The study of the neutron fields characteristics was conducted in the territory of the Beloyarsk nuclear power plant named after I.V. Kurchatov, Zarechniy, Russia. The Beloyarsk NPP is Russia's only power plant with power units of various types. The Beloyarsk NPP

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has 4 units. Units 1, 2 with reactor facilities AMB-100 and AMB-200 were launched in 1964 and 1967 and closed in 1981 and 1989, respectively. Unit 3 with a fast breeder reactor BN-600 was launched in 1980 and unit 4 with a fast breeder reactor BN-800 was launched in 2016. Since units 1 and 2 have been under permanent shutdown for at least 30 years, nowadays used nuclear fuel removal operations are being carried out. Thus, occupational neutron exposure is taking place during the packaging of spent nuclear fuel. Units 3 and 4 have fast breeder reactor facilities which are different from the others as the fission of nuclear fuel (Pu oxide and $^{238}$U oxide) there goes under fast neutrons. Even though a form of the neutron spectrum behind the biological protection might be simulated, it still requires an experimental verification because some inhomogeneities in the biological protection cause local areas with a high neutron dose. Such anomalies were found in the rooms adjacent to the reactor, particularly fresh subassembly drum rooms located at units 3 and 4. Reactor preventive maintenance involves calibration of detectors placed inside the reactor. As the detectors should be calibrated exactly in the same geometry they use, calibration is done by placing a calibration source inside the reactor.

The third way of neutron exposure is exposure to fresh or spent nuclear fuel. Since a fast breeder reactor was constructed to solve the problem with spent nuclear fuel from reactors with thermal neutrons, fresh nuclear fuel for breeders contains not only natural uranium but also accumulated actinoids undergoing spontaneous fission with neutron emission. Since any neutron energy distribution measurements have never been performed for commercial fast breeder reactors, such study is undoubtedly of considerable interest.

Neutron dose estimations were obtained by taking several measurements intended to:

1) Derive energy distribution of the neutron fluence;
2) Estimate the reference value of the ambient dose equivalent rate;
3) Estimate directional distribution of the neutron angular fluence rate;
4) Derive the reference value of the personal dose equivalent rate;
5) Compare dosimeter readings with the reference values of radiation protection quantity.
6) Estimate site-specific correction factors for both personal dosimeters and survey meters.

The neutron fields at workplaces of the Beloyarsk NPP are studied in the present research. The energy and directional distribution of the neutron fields was determined. In order to obtain site-specific correction factors, measurements of H*(10) rate with survey meters and Hp(10) with personal dosimeters, placed on a slab phantom, and assessment of the reference values of H*(10) rate and Hp(10) were taken.

## 2. Materials and methods

### 2.1. Measurement location

The measurements of H*(10) rate and neutron energy distribution were taken at 8 workplaces: near a transport cask inside a railway carriage at units 1–3 (locations 1, 3); in fresh subassembly drum rooms at units 3, 4 (locations 2, 4); inside a protective cover near a small rotating plug at unit 4 (location 5); in the reactor hall at unit 4 (location 6) and near two types of fresh fuel in fresh nuclear fuel storage facility at unit 4 (location 7, 8).

**Fig. 1.** Dosimeter-radiometer DKS-96 with a BDKN-96 detection unit (left) and AT1117 M radiation monitor with a BDKN-03 detection unit (right).

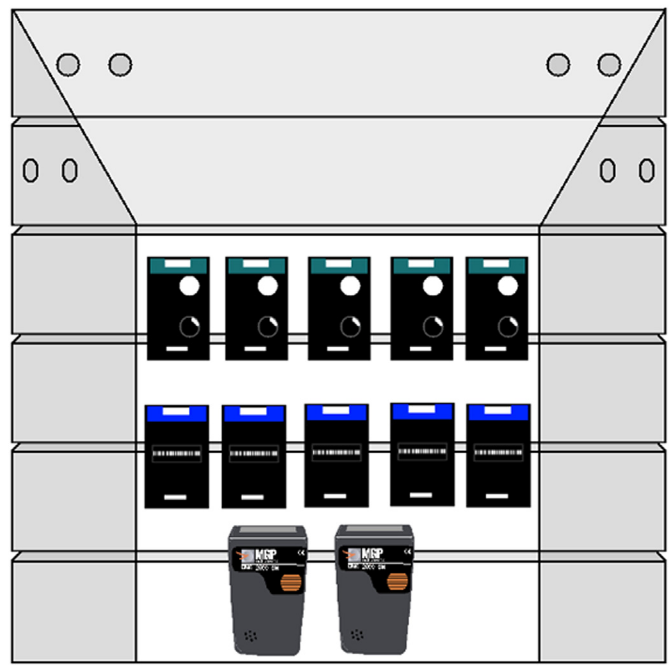

**Fig. 2.** Disposition of the thermoluminescent and electronic direct reading dosimeters on the slab phantom.

**Fig. 3.** AT1117 M spectrometer with the BDKN-06 unit and the set of spheres.

**Table 1**
Fluence-average neutron energy, average h*(10), reference value of ambient dose equivalent rate, reference value of neutron fluence rate for chosen locations.

| Location | Type and place of work | Spectrum mean energy, keV | $h^*(10)$, $pSv\cdot cm^2$ | $\dot{H}^*(10)$, $\mu Sv/h$ | $\phi$, $cm^{-2}s^{-1}$ |
|---|---|---|---|---|---|
| 1 | Units 1.2. Transport cask inside the railway carriage | 558 | 215 | 8.3 | 10.8 |
| 2 | Unit 3. Fresh subassembly drum | 0.01 | 12 | 2.3 | 53 |
| 3 | Unit 3. Transport cask inside the railway carriage | 331 | 143 | 11 | 21 |
| 4 | Unit 4. Fresh subassembly drum | 64 | 23 | 114 | 1383 |
| 5 | Unit 4. Protective cover | 0.028 | 12 | 1.1 | 26 |
| 6 | Unit 4.$^{252}$Cf source in the reactor hall | 1092 | 259 | 1342 | 1440 |
| 7 | Unit 4. Fresh nuclear fuel storage facility (MOX fuel) | 759 | 222 | 26 | 32 |
| 8 | Unit 3. Fresh nuclear fuel storage facility (Pu fuel) | 1041 | 221 | 7.0 | 8.8 |

**Table 2**
Average $h_p$ (10) conversion coefficients for chosen locations.

| Location | $h_p(10, 0°)$, $pSv\cdot cm^2$ | $h_p(10, 45°)$, $pSv\cdot cm^2$ | $h_p(10, 90°)$, $pSv\cdot cm^2$ | $h_p(10, 135°)$, $pSv\cdot cm^2$ | $h_p(10, 180°)$, $pSv\cdot cm^2$ |
|---|---|---|---|---|---|
| 1 | 256 | 212 | 13 | 12 | 23 |
| 2 | 9 | 6 | 0.4 | 1.1 | 1.2 |
| 3 | 174 | 140 | 7.3 | 7.1 | 13 |
| 4 | 23 | 18 | 2.3 | 2.8 | 4.2 |
| 5 | 9 | 6 | 0.4 | 1.0 | 1.2 |
| 6 | 295 | 262 | 31 | 29 | 52 |
| 7 | 254 | 222 | 21 | 20 | 36 |
| 8 | 248 | 225 | 31 | 29 | 51 |

### 2.2. Measurement campaign

Neutron ambient dose equivalent was measured with survey meters to identifying workplaces, where personal neutron monitoring is required and for reference value of ambient dose rate estimation. Survey measurements were done with a dosimeter-radiometer DKS-96 with a BDKN-96 detection unit [9] and an AT1117 M radiation monitor with a BDKN-03 detection unit [10]. The image of survey meters is shown in Fig. 1. The DKS-96 with the BDKN-96 detection unit consists of a $^3$He proportional counter placed inside a 3.5 cm polyethylene moderator. The AT1117 M with the BDKN-03 detection unit contains also a $^3$He proportional counter with a 10 cm polyethylene moderator.

Personal neutron dosimeters, namely thermoluminescent dosimeters (Harshaw 7776/8814 and Harshaw 6776/8806 [11]) and electron direct reading dosimeters MGP DMC 2000 GN [12], were used to determine personal dose equivalent. Harshaw 7776/8814 is used to measure lens dose, Hp(3), deep dose, Hp(10), Hp(0.07) and contains four detectors LiF:Mg,Ti, while three of them are enriched with $^7$Li and placed under different filtrations, and only one with $^6$Li. Harshaw 6776/8806 is used only for gamma and neutron personal dose equivalent measurement (Hp(10). There are four detectors LiF:Mg,Ti, but two of them are enriched with $^7$Li and another two with $^6$Li. Neutron and gamma personal dose equivalent was calculated automatically with a Harshaw automated reader instrument. Personal neutron dosimeters were placed on the tissue equivalent slab phantom during measurements (Fig. 2).

The neutron spectra measurements were taken with the AT1117 M radiation monitor which has the BDKN-06 detection unit [13,14] and a set of spheres (Fig. 3). AT1117 M contains a $^3$He counter and the set of polyethylene spheres from 3 up to 12 inches to measure neutrons from thermal energies up to 16 MeV. To unfold spectrum, the algorithm, described in Ref. [15], was used. The unfolded spectrum was divided into 34 energy bins. The statistical error of the measured count rates did not exceed 20%.

The information about neutron energy distribution was used to calculate the reference neutron fluence rate value - $\phi$ obtained as a sum of the fluence rate in each energy bin.

The energy distribution information was used to determine the average fluence to ambient dose equivalent conversion coefficient, h*(10), for each measurement location using equation (1).

$$h^*(10) = \frac{\sum_i h^*(10)_i \cdot \phi_i}{\sum_i \phi_i} \tag{1}$$

where $\phi_i$ – neutron fluence rate in the i-th energy bin. The value for conversion coefficient in i-th energy bin was taken from ICRP/ICRU conversion coefficients [16,17]. The same approach was used to obtain an average value for the conversion coefficients for the personal dose equivalent. The $h_p$ (10,θ) was calculated using the data [18,19].

The reference ambient dose equivalent rate value was obtained with using the neutron energy distribution and fluence to ambient dose equivalent conversion coefficient in accordance with equation (2).

$$\dot{H}^*(10) = \sum_i h^*(10)_i \cdot \phi_i \tag{2}$$

The directional distribution of neutron angular fluence was estimated using both active and passive personal dosimeters mentioned above by placing them on four faces of the slab phantom, namely front, back, left and right. The dosimeters readings were used to estimate directional distribution. It was suggested the sum of all the readings from one dosimeter type in one location represents 100% of the neutron fluence rate. Therefore, it was assumed the dosimeter at the front measured only the neutrons originating from the front and none originating from the side or back. The fluence from the phantom bottom and top was not estimated. To overcome this limitation, the fluence from the top and bottom were assumed to be zero. Partial fluences incident in the directions other than the measurement angles on the phantom were estimated using linear interpolation in steps of 45° in perpendicular directions.

In this study, it is suggested the neutron energy distribution is the same in each direction. This assumption was made because

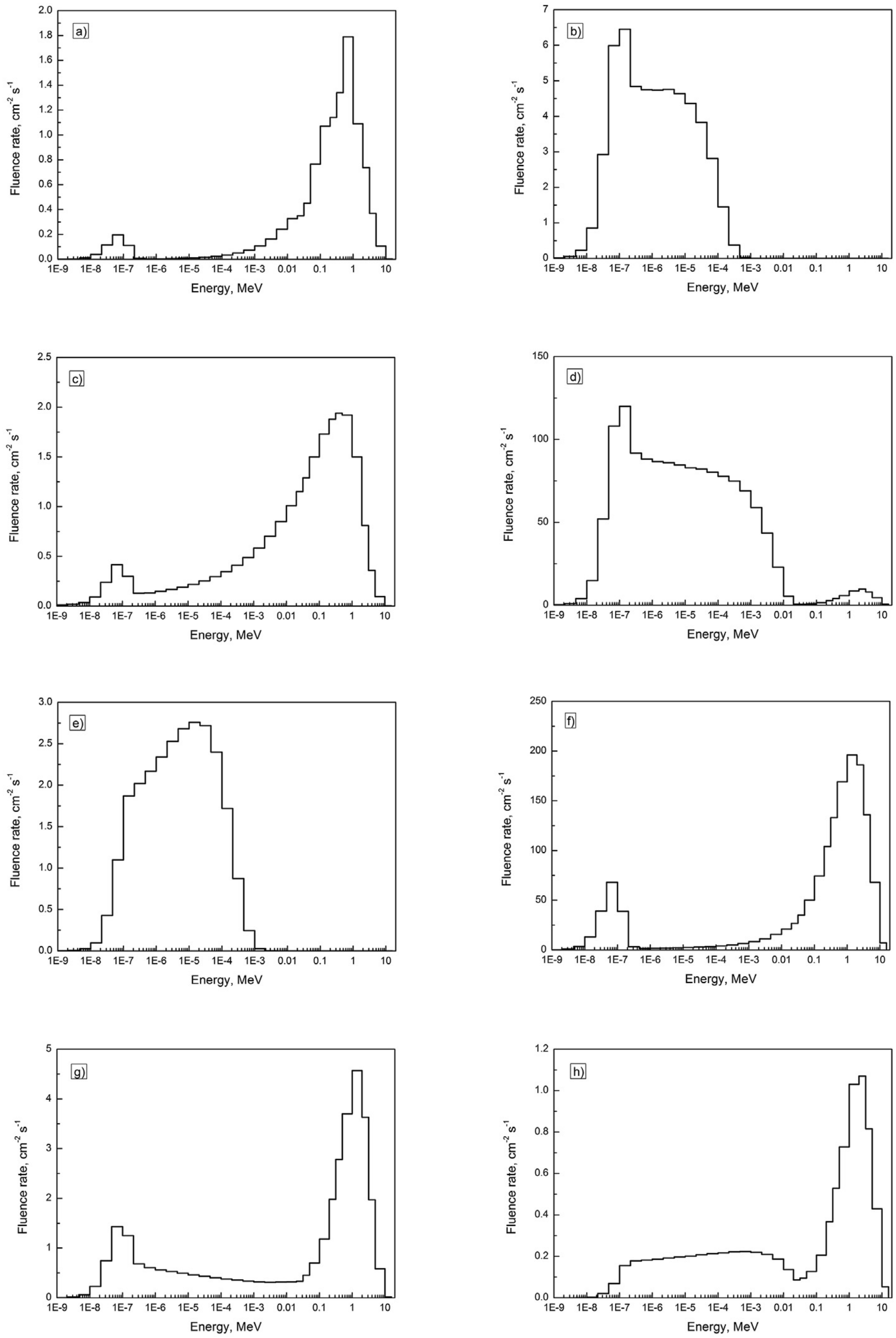


**Fig. 4.** Neutron spectra of workplaces: a) Units 1,2. Transport cask inside the railway carriage; b) Unit 3. Fresh subassembly drum; c) Unit 3. Transport cask inside the railway carriage; d) Unit 4. Fresh subassembly drum; e) Unit 4. Protective cover; f) Unit 4.$^{252}$Cf source in the reactor hall; g) Unit 4. Fresh nuclear fuel storage facility (MOX fuel); h) Unit 4. Fresh nuclear fuel storage facility ($^{239}$Pu fuel).

directional spectrometry was not available. Assuming that the energy distribution remains the same in all directions was the only way possible. Another assumption made in the research is a ‘static condition’, meaning a person present in a certain location is not moving.

The determination of the reference personal dose equivalent rate value was performed in correspondence with equation (3).

$$\dot{H}_p(10,\theta) = \sum_{\theta} \phi(\theta) \cdot h_p(10,\theta) \quad (3)$$

where θ - the angle of neutron fluence rate coming.

The values obtained were compared with each other and with the readings of the personal dosimeters to evaluate the behavior of the dosimeters in the locations of interest.

## 3. Results

### 3.1. Neutron fields characteristics

All measurements were done in the rooms of the Beloyarsk NPP. After analyzing the workplaces, those were selected, where the ambient dose equivalent was above 0.5 μSv/h. Ambient dose equivalent was measured at more than 20 workplaces of energy

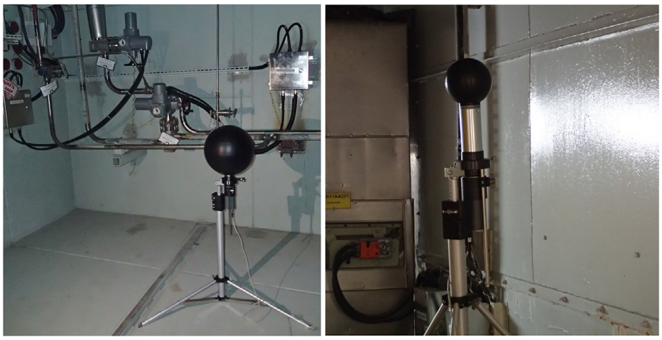

**Fig. 5.** Spectrometer placing: near the fittings in the room adjacent to the reactor core (left photo) and beside the reactor core shielding (right photo).

units 1–4 of the Beloyarsk NPP, but only 8 workplaces had satisfied conditions. Tables 1 and 2 give fluence-average neutron energy, average h*(10), the reference value of ambient dose equivalent rate, the reference value of neutron fluence rate, and average $h_p$ (10) conversion coefficients.

### 3.2. Neutron energy distribution

The obtained neutron spectra are shown in Fig. 4. It can be seen there is only one workplace with neutron exposure at units 1 and 2. These workplaces are around transport cask inside the railway carriage. It is explained by the permanent shutdown of units 1 and 2, therefore, neutrons might appear only from spent nuclear fuel. In the case of fast breeder reactors BN-600 (unit 3) and BN-800 (unit 4) neutron exposure takes place at fresh nuclear fuel assemblies' storage, during manipulating neutron radionuclide source; beside a reactor wall, whilst working with spent nuclear fuel, etc. Some photos of spectra measurements are shown in Fig. 5. It can be easily noted neutron spectra have different forms, neutrons peak positions, and intensities. All these characteristics have a great influence on neutron occupation exposure and have a significant contribution to uncertainties in neutron dose estimation.

### 3.3. Ambient dose equivalent measurement

The results of the measured ambient dose equivalent rates and its reference value are represented in Table 3. The represented uncertainties over the measured values in Table 3 are given by the manufacturer and usually equal to 20–25%. It can be notice that in most cases the ambient dose equivalent rate is overestimated. It can be explained by the fact that it has an over-response in the intermediate energy level. Fig. 6 shows the H*(10) responses of the survey meters normalized on a$^{239}$PuBe calibration source [18]. In some cases, where the measured H*(10) rate is smaller than the reference value, there is no exact explanation.

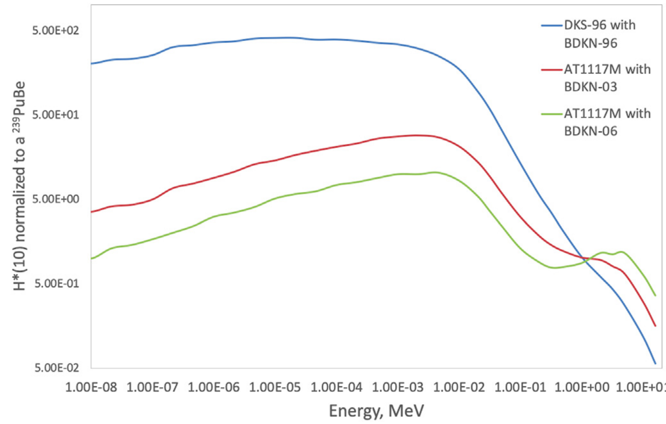


**Fig. 6.** H*(10) response of the survey meters normalized on $^{239}$PuBe calibration source.

### 3.4. Direction distribution

To estimate the direction distribution of neutron fluence, personal dosimeters were placed on the four faces of the slab phantom. The measured values from all the dosimeters are represented in Table 4, including their uncertainties. The uncertainties take into account standard deviation from various detectors of the same type placed on the same side of the phantom. Uncertainties specified by the manufacturer are also considered. The personal dose equivalent was not measured inside the storage of fresh nuclear fuel assemblies due to the regulatory. Placement of a hydrogen-consisting material inside fresh nuclear fuel storage is forbidden. There are some differences among the results from the various dosimeters because of different energy responses that different detector types have. Both Harshaw and DMC 2000 GN dosimeters were calibrated with $^{239}$Pu source as well as survey meters.

Assuming that the sum of all readings from one detector type represents 100% of the neutron fluence and that the energy spectrum remains constant in all orientations, linear interpolation was used to calculate the relative neutron fluence incident in different directions on the phantom.

Table 5 shows the findings of this interpolation. The directional distribution at location 5 was obtained with only one type of the dosimeters. It is demonstrated the main resource of coming neutrons at locations 2, 3, and 6 is the phantom's front direction. Furthermore, at locations 4 and 5 neutrons come mainly from the right. At location 1, the neutron fluence rate can be considered isotropic.

### 3.5. Reference value for the personal dose equivalent rate

The reference values for the personal dose equivalent rate were calculated using information about the angular distribution of

**Table 3**
Results of the measured ambient dose equivalent rates and their reference values.

| Location | $\dot{H}^*(10), \mu Sv/h$ | | | |
|---|---|---|---|---|
| | DKS-96 with BDKN-96 | AT1117 M with BDKN-03 | AT1117 M with BDKN-06 | The reference value |
| 1 | 44 ± 11 | 2.9 ± 0.6 | 10.9 ± 2.2 | 8.3 |
| 2 | 42 ± 11 | 2.0 ± 0.4 | 7.6 ± 1.5 | 2.3 |
| 3 | 3.7 ± 0.9 | 3.7 ± 0.7 | 14.5 ± 2.9 | 11 |
| 4 | 1400 ± 350 | 120 ± 24 | 535 ± 107 | 114 |
| 5 | 58 ± 15 | 2.0 ± 0.4 | 5.6 ± 1.1 | 1.1 |
| 6 | 2500 ± 625 | 2550 ± 510 | 1779 ± 356 | 1342 |
| 7 | 14 ± 4 | 20 ± 4 | 37 ± 7 | 26 |
| 8 | 8.6 ± 2.2 | 2.6 ± 0.7 | 10 ± 2 | 7.0 |

**Table 4**
Results of the measured personal dose equivalent rates using the slab phantom.

| Location | Position on the phantom | $\dot{H}_p(10), \mu Sv/h$ | | |
|---|---|---|---|---|
| | | Harshaw 7776/8814 | Harshaw 6776/8806 | DMC 2000 GN |
| 1 | Front | 34 ± 11 | 29 ± 9 | 1.6 ± 0.4 |
| | Back | 24 ± 9 | 15 ± 5 | 0.43 ± 0.14 |
| | Left | 35 ± 11 | 13 ± 4 | 0.9 ± 0.3 |
| | Right | 24 ± 7 | 26 ± 8 | 0.8 ± 0.2 |
| 2 | Front | 513 ± 154 | 309 ± 93 | 4.6 ± 1.3 |
| | Back | 203 ± 61 | 118 ± 35 | – |
| | Left | 209 ± 63 | 152 ± 46 | 7.2 ± 1.9 |
| | Right | 283 ± 85 | 216 ± 65 | 5.1 ± 1.2 |
| 3 | Front | 77 ± 25 | 46 ± 15 | – |
| | Back | 42 ± 21 | 22 ± 7 | – |
| | Left | 38 ± 12 | 15 ± 4 | – |
| | Right | 76 ± 23 | 24 ± 7 | – |
| 4 | Front | 3712 ± 1115 | 2267 ± 692 | 177 ± 35 |
| | Back | 1931 ± 605 | 1322 ± 415 | 123 ± 25 |
| | Left | 1726 ± 518 | 1306 ± 392 | – |
| | Right | 6091 ± 1827 | 4040 ± 1212 | – |
| 5 | Front | 78 ± 23 | 66 ± 24 | 6.3 ± 1.3 |
| | Back | – | 69 ± 21 | 4.4 ± 0.9 |
| | Left | – | 32 ± 10 | – |
| | Right | – | 241 ± 72 | – |
| 6 | Front | 4174 ± 1315 | 2517 ± 769 | 1600 ± 347 |
| | Back | 1598 ± 577 | 1083 ± 336 | 933 ± 213 |
| | Left | – | 1667 ± 500 | – |
| | Right | 2333 ± 700 | 1600 ± 480 | – |

**Table 5**
Results from the relative neutron fluence incident in different directions on the phantom using linear interpolation.

| Angle of upcoming neutrons | Location | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| | Direction distribution and its uncertainty, % | | | | | |
| 0° | 15 ± 1 | 20 ± 1 | 19 ± 3 | 13 ± 1 | 8 | 22 ± 4 |
| 45° | 14 ± 1 | 16.00 ± 0.02 | 16.00 ± 0.01 | 18.0 ± 0.3 | 19 | 18 ± 3 |
| 90° | 12 ± 2 | 13 ± 1 | 14 ± 3 | 23.00 ± 0.01 | 30 | 13 ± 1 |
| 135° | 12 ± 2 | 10.0 ± 0.2 | 12 ± 1 | 15.0 ± 0.1 | 19 | 11 ± 1 |
| 180° | 12 ± 2 | 8.0 ± 0.5 | 10 ± 1 | 7.0 ± 0.1 | 8 | 9 ± 1 |
| −135° | 11 ± 1 | 9.00 ± 0.01 | 9.00 ± 0.01 | 7.0 ± 0.3 | 6 | 7 ± 3 |
| −90° | 11 ± 4 | 9.0 ± 0.5 | 7 ± 1 | 7.0 ± 0.4 | 4 | 6 ± 6 |
| −45° | 13 ± 2 | 15.0 ± 0.2 | 13 ± 1 | 10.0 ± 0.1 | 6 | 14 ± 1 |

neutron fluence. Personal dosimeters were placed on the slab phantom for a certain time to get reliable data. It was supposed the spectrum remains unchanged regardless of direction because directional spectrometry was not available.

The results of the partial and total personal dose equivalent rate and the reference value for the personal dose equivalent rates are shown in Table 6.

**Table 6**
Results of the partial and total personal dose equivalent rate and the reference value for the personal dose equivalent rates.

| Angle of upcoming neutrons | Location | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| | $\dot{H}_p(10, \theta), \mu Sv/h$ | | | | | |
| 0° | 1.51 | 0.35 | 2.50 | 15 | 0.07 | 337 |
| 45° | 2.20 | 0.36 | 3.14 | 25 | 0.14 | 429 |
| 90° | 0.12 | 0.02 | 0.12 | 3 | 0.013 | 31 |
| 135° | 0.11 | 0.04 | 0.11 | 3 | 0.02 | 28 |
| 180° | 0.06 | 0.02 | 0.10 | 2 | 0.010 | 24 |
| The reference value | 3.99 | 0.78 | 6.0 | 48 | 0.25 | 848 |

### 3.6. Site-specific correction factors

Site-specific correction factors are suggested by comparing the reference values with the personal dosimeters readings. The dosimeters readings in front of the phantom were compared with the values of the dose equivalent rates. The comparison of dose rates between personal neutron dosimeters (Harshaw 6777/8814. Harshaw 6776/8806. DMC 2000 GN), radiation monitor (AT1117 M with BDKN-03 unit) and true value are shown in Table 7. Thus, it is clearly seen that the site-specific correction factors lie in a wide range from 0.0015 up to 3. It means the reference quantity might be as overestimated up to hundreds of times as underestimated up to 3 times.

## 4. Conclusion

The analysis of the neutron fields at workplaces in the territory of the Beloyarsk NPP was carried out. About 20 workplaces or types of works were distinguished but only 8 of them were of research interest. To improve the system of personal monitoring, it is vital to obtain the reference values of H*(10) rate and Hp(10). In all

**Table 7**
Site-specific correction factors of different instruments for the Beloyarsk NPP workplaces.

| Location | Site-specific correction factor | | | | | |
|---|---|---|---|---|---|---|
| | Harshaw-8806 | Harshaw-8814 | DMC 2000 GN | DKS-96 with BDKN-96 | AT1117M with BDKN-03 | AT1117 M with BDKN-06 |
| 1 | 0.14 | 0.12 | 2.5 | 0.2 | 2.9 | 0.8 |
| 2 | 0.003 | 0.0015 | 0.2 | 0.05 | 1.2 | 0.3 |
| 3 | 0.13 | 0.08 | – | 3.0 | 3.0 | 0.8 |
| 4 | 0.02 | 0.013 | 0.3 | 0.08 | 0.95 | 0.2 |
| 5 | 0.004 | 0.003 | 0.04 | 0.02 | 0.6 | 0.2 |
| 6 | 0.3 | 0.2 | 0.5 | 0.5 | 0.5 | 0.8 |

measured locations, spectra were divided into two types: 'hard' and 'soft'. 'Hard' spectra contain a significant contribution of the fast neutrons (E > 0.5 MeV) that can be easily noticed by the peak in the high neutron energy region. Such spectra are characteristic of radionuclide sources, fresh and spent nuclear fuel. 'Soft' spectra are most common for rooms adjusted to the reactor core, in other words, they are placed behind the biological shielding. Such spectra contain mostly scattered neutrons, having energy under 0.5 MeV. As far as spectral measurement at fast breeder reactors has never been done before, this research is valuable.

The directional distribution of the neutron fluence rate was measured by placing personal dosimeters in four faces of the slab phantom. It was found out neutron fields have primary direction in most of the measurement locations. At one location neutron field was isotropic. Taking into account the directional distribution of the neutron fluence rate, the reference value of Hp(10) was calculated using hp (10,$\theta$) conversion coefficients for each of 5 angles ($0^\circ$, $45^\circ$, $90^\circ$, $135^\circ$, and $180^\circ$). The obtained values were compared with the personal dosimeters readings to determine the site-specific correction factors. One can notice that without directional distribution personal dosimeters overestimate personal dose equivalent from tens up to hundreds of times. This work presents results that demonstrate the complexity and care necessary to do measurements in the neutron fields at workplaces of NPPs. The characteristics knowledge of the neutron energy and directional distribution are essential to ensure the safety of radiation hazardous facilities.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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